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Simulation of Optimal Operation of a Multiple Wells Open Geothermal System

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Abstract. Geothermal energy is a promising type of renewable energy. To analyze and improve the efficiency of the system, a three-dimensional mathematical model of an open geothermal loop system is developed. The proposed model takes into account thermophysical characteristics of the geothermal aquifer and the most important technical parameters of the wells. The pump pressures in producing and injection wells, as well as the distances between these wells are considered as parameters to be optimized in terms of achieving the longest period of effective operation of the geothermal loop. The results of numerical calculations are discussed.

1. Introduction

In Russia, the most perspective geothermal resources are in the Central, North-Western, Ural, Southern and North-Caucasian Federal Districts, the West Siberian Plain, the Krasnoyarsk Territory, Chukotka, Sakhalin, and others. All these resources are now practically not used, there are only a few examples. In the paper an open geothermal loop consisting of two or three wells is considered as a geothermal cyclic system (GCS). To describe the system of wells operating, including the injection and producing wells with cold and hot water, respectively, a 3D model is suggested on the basis of works on underground hydrodynamics [1] and water filtration in a porous soil, but taking into account the geothermal flow [2-5]. The main attention is paid to the selection of optimal parameters for the operation of such systems to increase the timing of the GCS operation. The operation of the GCS is terminated when the temperature of the producing water $T_2(t)$ becomes less than a certain predetermined value, or when the temperatures of the injected water $T_1(t)$ and $T_2(t)$ become equal, i.e. the front of cold water from the injection wells reaches the production well. For example, in Paris countryside there are 37 pairs (doublets) of wells that, due to geothermal sources, supply more than 0.5 million people and enterprises with heat and hot water during more than 30 years.



2. Mathematical model and numerical algorithm

The heat transfer in the geothermal aquifer is carried out in two ways: convection and diffusion. Figure 1 presents a diagram of the GCS open loop operation consisting of two injection wells (blue color) and one producing well (red color).

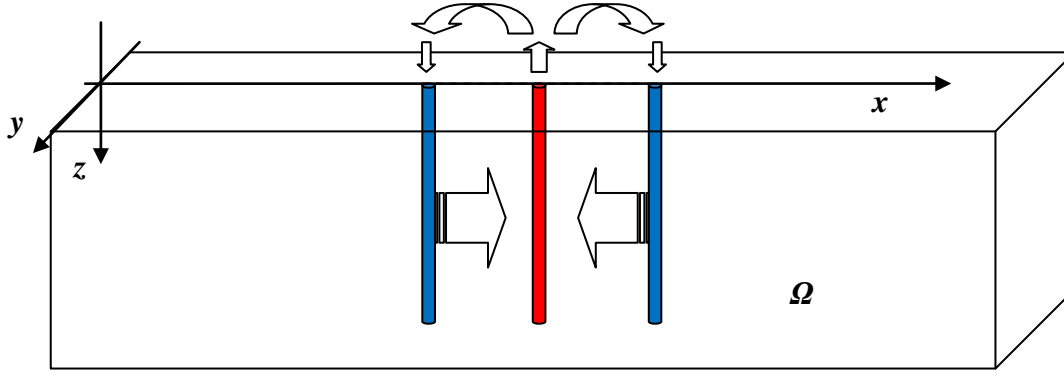


Figure 1. A geothermal open loop system with three wells.

When describing the heat transfer and water filtration processes in a thermal reservoir, which takes into account the Darcy law and the mass conservation law (continuity equation) forming in general case a system of equations allowing to find the pressure distribution and the velocity field of water filtration in the soil. The equation for the pressure $p=p(t,x,y,z)$ is a partial differential equation related to Laplace equation describing the distribution of an electric field potential. In the case of a homogeneous medium it is reduced to Laplace equation. As a result, the process of heat propagation $T=T(t,x,y,z)$ in the aquifer (in the computational region Ω) is described by the following equation [4]:

$$\frac{\partial T}{\partial t} + b \left(\frac{\partial T}{\partial x} u + \frac{\partial T}{\partial y} v + \frac{\partial T}{\partial z} w \right) = \lambda_0 \Delta T, \quad (1)$$

which is considered together with the equations for the components of the fluid filtration rate $V=(u,v,w)$

$$\begin{cases} \frac{\partial u}{\partial t} = -\frac{1}{\rho} \frac{\partial p}{\partial x} - \frac{g\sigma u}{k} \\ \frac{\partial v}{\partial t} = -\frac{1}{\rho} \frac{\partial p}{\partial y} - \frac{g\sigma v}{k} \\ \frac{\partial w}{\partial t} = -\frac{1}{\rho} \frac{\partial p}{\partial z} - \frac{g\sigma w}{k} - g, \end{cases} \quad (2)$$

taking into account the continuity equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0, \quad (3)$$

$$\lambda_0 = \frac{\kappa_0}{\rho_0 c_0 (1-\sigma) + \rho c_f \sigma}, \quad b = \frac{\sigma \rho c_f}{\rho_0 c_0 (1-\sigma) + \rho c_f \sigma}, \quad \text{where } \rho_0 \text{ and } \rho \text{ are the soil and the water density in}$$

the aquifer, c_0 and c_f are specific heat of the soil and the water, σ and κ_0 are porosity and heat conductivity of the soil, respectively.

The equations (1)-(4) for temperature and pressure in aquifer are solved using a finite difference method based on an approach of works [6-8]. Note that the computational area Ω with the aquifer is large enough to avoid the effect of boundary conditions at the lateral boundaries.

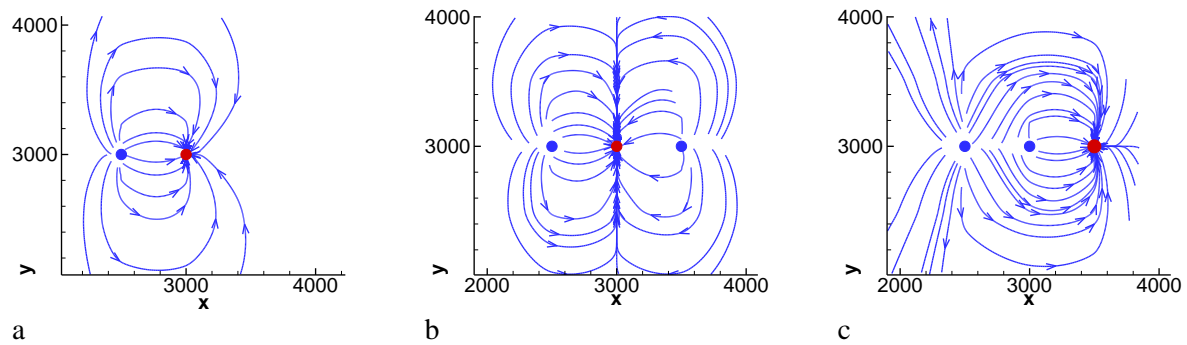


Figure 2 The streamtraces of the water filtration in the aquifer in a horizontal plane from the injection wells (blue points) to the producing well (red point) for different wells system.

3. Numerical results

To investigate operation of an open geothermal loop system we chose wells lineup consisting of one producing well and one or two injection wells. Producing well extracts the hot water from an aquifer by a pump, than the water is distributed to consumers, becomes colder and is returned by an injection well or wells into the aquifer. We have to explore how the pump pressure and distance between the wells influence the life time of the geothermal system. Numerical simulations are carried out for GCS, consisting of two wells (producing and injection) and a line of three wells (producing and two injection wells).

Figure 2 illustrates the water moving from injection to producing well, showing the streamtraces of the water filtration in the aquifer in a horizontal plane. The blue and red points denote the injection and producing wells. The water filtration gives a significant proportion in heat transfer in the aquifer comparing to the heat conductivity process in a media. The flows depend on the one hand of the wells arrangement and distance and, on the other hand, of the pumps capacity and the pressure generated in the wells.

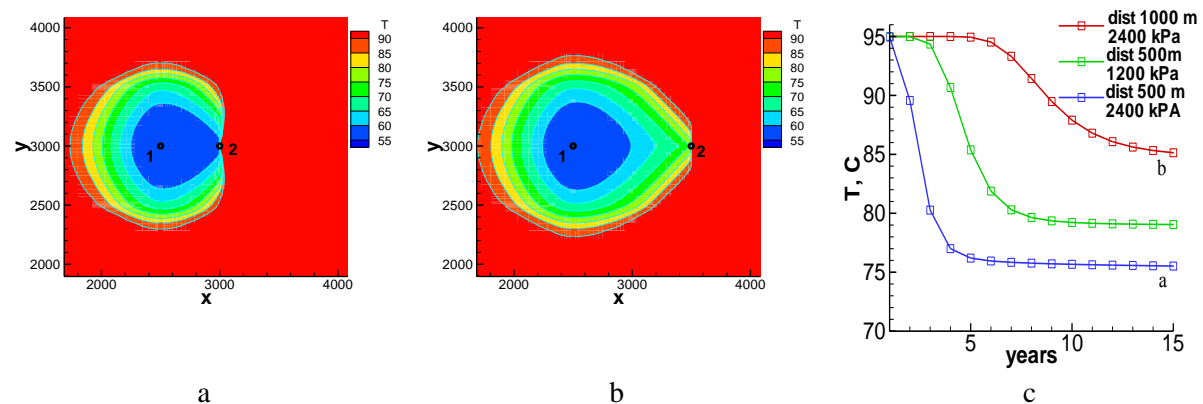


Figure 3. Temperature field after the 15th year of operation (a and b) in horizontal slice of the aquifer with the system of two wells. Points 1 and 2 are the injection and producing wells, respectively. Figure 3c shows the temperature variation profiles in the producing well during 15 years of operation.

Let the initial temperature of the considered aquifer be 95°C , the released cold water temperature be 55°C . The basic thermal parameters of the aquifer are as follows: soil thermal conductivity is 2.00 W/mK , soil volumetric heat is $2150 \text{ kJ/m}^3 \text{ K}$, porosity is 0.241 , filtration rate is $1.7 \cdot 10^{-5} \text{ m/s}$. We used an implicit finite difference method with splitting by the spatial variables in three-dimensional domain to solve the problem [6-8]. Sizes of the area are $6000\text{m} \times 6000\text{m} \times 50\text{m}$. The GCS is in the center of the area. The computational time step is 1 day (86400 s) and the simulated period is 15 years.

In figures 3a-b and figures 4a-b the thermal fields in the aquifer is presented in a horizontal plane after the 15th year of operation. In figure 3 an open loop system of two wells is considered. Points 1 and 2 denote the injection and producing well, respectively. The pumps pressure difference between the injection and producing wells is 2400 kPa . In figures 3a and 3b, the distance between the wells is 500 m and 1000 m , respectively. The wedge of cold water has reached the closer well. The resulting temperature in the producing well is approximately is 75°C . In figure 3c the producing temperature is shown during the years of operation for both cases: red line corresponds to the 1000 m distance, while blue line corresponds to the 500 m distance. The green line in the middle shows the temperature for the lower pressure difference. The distance between the wells is more effective rather than the pressure reduction.

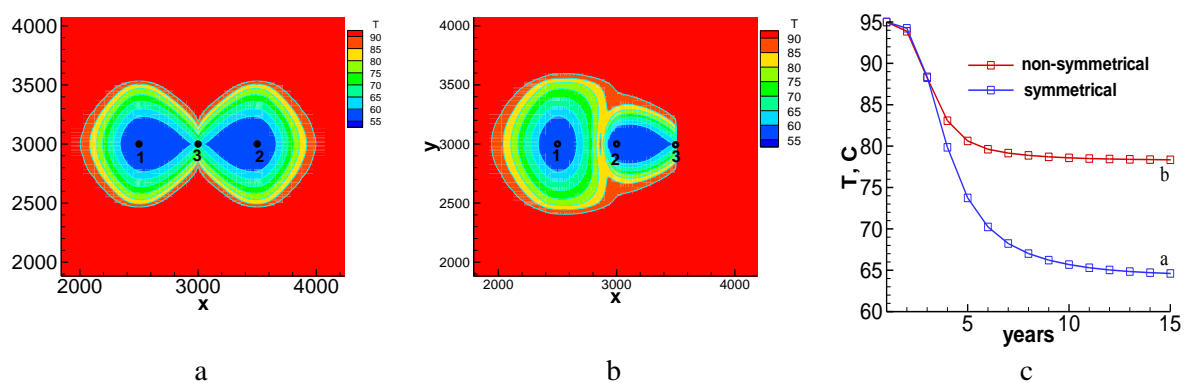


Figure 4. Temperature field in after the 15th year of operation (a and b) in horizontal slice of the aquifer with the system of three wells. Points 1, 2, and 3 are the two injection and one producing wells, respectively. Figure c shows the temperature variation profiles in the producing well during 15 years of operation for the cases a (blue line) and b (red line).

Let consider an open loop geothermal system consisting of three wells: two injection and one producing well. In figure 4 the temperature fields are presented in a horizontal slice of the aquifer with three wells open loop system. Points 1 and 2 correspond to the injection well with cold water and point 3 shows the producing well. The pump pressure in the producing well and the injection wells are 1200 and 600 kPa , respectively, so the pressure difference is 1800 kPa . In figure 4a the injection wells (points 1 and 2) with cold water are in the both sides from the producing well (point 3) at a distance of 500 m . The wedges of cold water reach the producing well from the both sides and do not allow using hot water intake of the aquifer effectively.

In figure 4b both injection wells are located in the left of the producing well. The distances between the wells are 500 m , and the same pumps with the same pressure difference as in figure 4a were used. The cold water from point 1 does not reach the producing well (point 3) and the producing well receives hot water from the right side of the aquifer. Figure 4c shows temperature dynamics in the producing well for two designs of the system, shown in figure 4a (symmetrical case, blue line) and figure 4b (non-symmetrical case, red line) during 15 years. Avoiding the discharge of cold water from both sides of the producing well allows more efficient use of the hot aquifer area.

4. Conclusion

The proposed model and the developed numerical algorithm allow carrying out simulations of temperature fields in an aquifer for various designs of open geothermal loops, consisting of two or three wells. The variation dynamics of temperature produced by hot water well depends on various parameters. For two wells system, the main parameters are the distance between the wells in the productive layer and the pressure difference. For the system, consisting of three wells (one producing and two injection wells), the relative position of these wells also have to be taken into account.

Acknowledgments

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